Stability of Accretion Disks in Presence of Nucleosynthesis

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ABSTRACT

We study the effect of nuclear reaction on a thin, axisymmetric, differentially rotating, inviscid, steady accretion flow around a black hole from an analytical point of view. We find that for most of the reasonable disk parameters, when $p-p$-reaction, dissociation of deuterium and helium are taken into account, the *transonic* region of the disk continues to have the inner sonic point and if the temperature of the flow at the injection point could be raised (by say, some heating processes) the flow would to pass through this inner sonic point. Otherwise, the flow may be unstable. We use the sonic point analysis to study the solution. In the rest of the disk parameters the inner sonic point is absent altogether and the flow will definitely be unstable.

Subject headings: Black holes – nucleosynthesis – disks: stability

1. Introduction

Black hole accretion flow can reach a temperature of about $T_{virial} = \frac{1}{k}\frac{GM_{BH}m_p}{r_g} \sim 5.2 \times 10^{12}$K if no cooling processes are included. Here, $r_g = 2GM_{BH}/c^2$ is the gravitational radius of a black hole, k is the Boltzmann constant, G is the Gravitational constant, M_{BH} is the mass of the black hole, m_p is the mass of the proton and c is the velocity of light. In a realistic flow, the temperature is smaller. For instance, in a Shakura-Sunyaev (1973) Keplerian disk, the temperature becomes close to a few times 10^7K. In a two-temperature transonic flow, the ions may remain hot ($T_p \sim 10^{8-11}$K) while the electrons may be cooler (($T_e \sim 10^{7-9}$K) depending on accretion rate of the Keplerian and sub-Keplerian components (Colpi, Maraschi & Treves, 1984; Chakrabarti & Titarchuk, 1995). Since temperature

inside a star is much less compared to the ion temperature mentioned above, considerable nucleosynthesis is expected inside an accretion disk. It is true that the free-fall timescale $t_{ff} \sim r v_{ff} \sim (\frac{r}{r_g})^{3/2} \frac{2GM_{BH}}{c^3}$ s is very small compared to the stellar age and density of gas inside an accretion disk, $\rho_d \sim \frac{\dot{M}_{Ed} t_g}{r_g^3} (\frac{r}{r_g})^{-3/2}$gm cm^{-3} is also very small compared to the stellar density but the reaction cross-sections are often very temperature sensitive ($\propto T^{4-16}$) and the higher temperature could compensate for the lower density.

Considerable work has been done in the past on nucleosynthesis inside a disk taken into consideration. Paczyński and Jaroszyński (1978) have studied the importance of nucleosynthesis at high temperature thin disks made up of Helium and Carbon. In these disks, electron degeneracy pressure supports gravity. Taam & Fryxell (1985) studied thin accretion disks of hydrogen-rich matter and showed that under certain condition, thermal instability of a Keplerian disk may totally disappear. They consider very high density disks where degenerate pressure in the mid-plane supports the disk structure. Chakrabarti, Jin & Arnett (1987) and Jin, Arnett & Chakrabarti (1989) studied nucleosynthesis in thick accretion disks of realistic density and temperature. These disks have very little radial velocity and a significant amount of nucleosynthesis was possible only if viscosity parameter of Shakura-Sunyaev (1973) is very low $\alpha_{ss} \lesssim 10^{-4}$. They showed that in order that *thin* disks remain stable against convection, only $p-p$ reactions are allowed in these disks in the radiation pressure supported regions. However, for hot thick disks, even CNO cycle would be allowed without destabilizing the disk. These results were later repeated by independent groups (Arai & Hashimoto, 1992; Hashimoto et al. 1993). More recently, Chakrabarti & Mukhopadhyay (1999) and Mukhopadhyay & Chakrabarti (2000) revisited the problem with a self-consistent accretion disk solution which includes heating and cooling. They find that nucleosynthesis in some range of the parameter space could be high enough to have an energy release or absorption by nuclear reaction comparable to the viscous heating. These studies are finding attention in recent years since one could detect lines from various isotopes from jets and companions and can, in principle, have some estimate of the conditions around a black hole.

However, work mentioned above was purely numerical in nature and was mainly due to repeated use of two types of analysis: First, the steady state thermodynamic condition of a disk is determined by using fourth order Runge-Kutta method *without* nucleosynthesis taken into account. Using temperature and density distributions thus obtained at each point, nucleosynthesis code is run which mainly involves solving 255 linear equations simultaneously, one equation for each isotope. For each infinitesimal advancement of matter toward the black hole, nuclear composition was updated and energy release or absorption was computed locally. After one complete run, the energy release is incorporated into the hydrodynamic equations and the integration scheme using the Runge-Kutta method is carried out to have

updated thermodynamic conditions. This process is continued till convergence. In the present paper, our approach is completely different. We attack the problem analytically and estimate effects of nucleosynthesis by using sonic point analysis. This way the problem becomes fully self-consistent to begin with and no iterative step is needed. Presence of a saddle type sonic point is a necessary condition for a steady solution, but it is not sufficient. The flow must connect a black hole horizon with infinity. Of course, in order to have the problem under control, we chose only a few reactions which are likely to be very important, namely, the Proton-Proton and photo-dissociation of deuterium and helium. Since we are interested in stability, we considered only those reactions (both exothermic and endothermic) which change specific energy (either way) significantly. We, however, neglect viscous heating or possible radiative transfer effects.

In any successful model of the black hole accretion, a source of the soft photon and a hot, Comptonising cloud must be present. In our model, this Comptonising cloud is the inner part of the disk itself. For concreteness, we concentrate on this model of black hole accretion, namely, one in which the flow close to a black hole is transonic (this is a necessary condition for any model), but far away, it is sub-divided into Keplerian and sub-Keplerian components. According to the properties of the transonic disks (see, Chakrabarti & Titarchuk, 1995; and references therein) higher viscosity flow settles into the equatorial plane, while quasi-spherical flows with lower viscosity surround the Keplerian disk. Soft photons emitted from the Keplerian component are reprocessed by the electrons at the centrifugal pressure supported boundary layer and hard X-rays are emitted. Recent observational results strongly support the presence of Comptonising clouds close to a black hole (Mirabel & Rodriguez, 1999; Homan et al., 2000) which have properties very similar to our centrifugal pressure supported regions in the inner accretion disks.

We had to choose a particular model in order to compute the optical depth of matter through which soft photons are Comptonized. Since at high temperature, photo-dissociation is important one has to compute number of hard photons present in this inner disk. Ordinarily, photo-dissociation at a high temperature is taken for granted, but in the present situation, there are paucity of very hot photons since only few of them are emitted from the Keplerian component and even fewer are intercepted by the sub-Keplerian flow located ahead of the Keplerian disk. What is more, optical depth may be so low that most of the time these photons do not interact adequately with deuterium and helium. Because of this, we compute photon number density self-consistently from the emitted spectrum of a sub-Keplerian flow.

In the next Section, we present the basic hydrodynamic equations which govern the steady state flow and perform the sonic point analysis. We show that effect of the nuclear term is significant in changing topological properties of the flow. In §3, we show that number

of sonic points is larger in presence of nucleosynthesis. We present a complete global solution and show how it is modified in presence of nucleosynthesis. Finally, in §4, we draw our conclusions.

2. Model Equations

In what follows, we use the unit of distance (x) to be $r_g = 2GM_{BH}/c^2$, unit of velocity to be c and the unit of mass to be M_{BH}, where G, M_{BH} and c are the gravitational constant, mass of the black hole and the velocity of light respectively. We use Paczyński & Wiita (1980) potential $\phi(x) = -\frac{1}{2(x-1)}$ to describe the flow around a Schwarzschild black hole. The basic dimensionless hydrodynamic equations which govern the infalling matter in the steady state are given by:

(a) The radial momentum equation:

$$\vartheta \frac{d\vartheta}{dx} + \frac{1}{\rho}\frac{dP}{dx} + \frac{\lambda_{Kep}^2 - \lambda^2}{x^3} = 0, \tag{1a}$$

(b) The continuity equation:

$$\frac{d}{dx}(\Sigma x \vartheta) = 0, \tag{1b}$$

(c) The entropy equation:

$$\frac{2na\rho\vartheta h(x)}{\gamma}\frac{da}{dx} - \frac{a^2\vartheta h(x)}{\gamma}\frac{d\rho}{dx} = Q_{nuc}. \tag{1c}$$

We do not have an azimuthal momentum equation, since we assumed an inviscid flow where angular momentum is conserved. The sound speed is defined by, $a^2 = \frac{\gamma P}{\rho}$, where, P and ρ are the pressure and the density respectively and γ is the adiabatic index. Also, λ is the conserved specific angular momentum (in units of $2GM_{BH}/c$) of the infalling matter, λ_{Kep} is the specific angular momentum in a Keplerian disk, $\lambda_{Kep}^2 = \frac{x^3}{2(x-1)^2}$, Σ is the vertically integrated density, $h(x)$ is the half thickness of the disk [$\sim ax^{1/2}(x-1)$], $n = \frac{1}{\gamma - 1}$ is the polytropic index, Q_{nuc} is the height averaged heat generation/absorption due to the nuclear effect of the disk. In order to isolate the effect of nucleosynthesis alone, we neglect all the other heating/cooling terms. The factor Q_{nuc} may be positive or negative depending on whether net nuclear energy is locally exothermic or endothermic. In future, we plan to include viscous heating and radiative cooling terms.

The energy release rate for $p-p$ reaction is given by,

$$Q_{pp} = \frac{\rho_p^2}{2} < \sigma v >_{pp} q_{pp}, \tag{2}$$

where, $\rho_p = \rho N_{Av} X_p / A_p$ is the number density of protons. The energy absorption rate due to D and ^4He dissociation is,

$$Q_{disso} = \rho_i < \sigma v >_i q_i, \tag{3}$$

where, the number density of the ith species (proton, deuterium or helium for this case) is $\rho_i = \rho N_{Av} X_i / A_i$. N_{Av} is the Avogadro Number, X_i is the mass abundance and A_i is the mass number of the ith element and q_i is the Q-value of the corresponding reaction. The reaction rates have been taken from standard literature (e. g., Clayton, 1983). For simplicity, and in order that this work may be generalized even when a large number of nuclear species are considered, we can express this as,

$$< \sigma v >_i = exp(g_i), \tag{4}$$

where,

$$g_i = c_i^1 + c_i^2/t9 + c_i^3/t9^{1/3} + c_i^4 t9^{1/3} + c_i^5 t9 + c_i^6 t9^{5/3} + c_i^7 log(t9)$$

is a seven parameter family of functions (Thielemann, 1980). For different reactions, the constant coefficients c_is will be different. In our case, Q_{nuc} is the dimensionless height integrated nuclear energy generation rate $Q_{nuc} = (Q_{pp} + Q_d + Q_{He})h(x)$.

Using Eqs. (1b-1c), we eliminate all $\frac{d\rho}{dx}$ and $\frac{da}{dx}$ terms and get,

$$\frac{d\vartheta}{dx} = \frac{\frac{(\gamma-1)}{\vartheta}(Q_{pp} + Q_d + Q_{He}) + (\gamma+1)[\frac{1}{2(x-1)^2} - \frac{\lambda^2}{x^3}] - \frac{a^2(5x-3)}{x(x-1)}}{\frac{2a^2}{\vartheta} - (\gamma+1)\vartheta}. \tag{5}$$

At the sonic point, numerator and denominator both simultaneously should be zero, so,

$$\frac{2a^2}{\vartheta} - (\gamma+1)\vartheta = 0 \tag{6}$$

and

$$\frac{(\gamma-1)}{\vartheta}(Q_{pp} + Q_d + Q_{He}) + (\gamma+1)[\frac{1}{2(x-1)^2} - \frac{\lambda^2}{x^3}] - \frac{a^2(5x-3)}{x(x-1)} = f(a, \vartheta) = 0. \tag{7}$$

From (6), we can get the Mach number at the sonic point as,

$$M_c = \sqrt{\frac{2}{\gamma+1}}. \tag{8}$$

From (7) and (8) we can obtain the sound speed at the sonic point.

The energy and entropy at the sonic points are expressed as,

$$E_c = \frac{1}{2}v_c^2 + na_c^2 - \frac{1}{2(x_c-1)} + \frac{\lambda_c^2}{2x_c^2}, \tag{9}$$

$$\dot{\mathcal{M}} = a_c^{(2n+1)} {x_c}^{3/2}(x_c-1)v_c. \tag{10}$$

Unlike the case of a flow with conserved energy (Chakrabarti, 1989; hereafter C89) one cannot compute everything about the flow using only two parameters, i.e., energy and specific angular momentum. In the present context of nuclear energy generation, one requires to supply the accretion rate as well which in turn determines the density of the flow. This is explicitly needed in eq. (7) above.

During the infall of matter, rate of change of mass fraction for proton, deuterium and helium can be written as,

$$-\frac{dX_p}{dt} = -\vartheta\frac{dX_p}{dx} = X_p exp(g_{pp})\rho - \frac{X_d exp(g_d)}{2}, \tag{11}$$

$$-\frac{dX_d}{dt} = -\vartheta\frac{dX_d}{dx} = X_d exp(g_d) - \frac{X_{He} exp(g_{He})}{2} - X_p exp(g_{pp})\rho, \tag{12}$$

$$-\frac{dX_{He}}{dt} = -\vartheta\frac{dX_{He}}{dx} = X_{He} exp(g_{He}). \tag{13}$$

During the Runge-Kutta integration, these linear differential equations are also solved simultaneously to obtain their mass fractions at each point.

3. Calculation of Photon Number Density

Before we present results of our global analysis, we like to spend some time on how the photon number density is computed inside the transonic flow. Usual treatment of photo-dissociation in the literature assumes the presence of a black body radiation in the flow. However, advective flow close to a black hole is likely to be optically thin, and they would intercept soft photons from Keplerian disks located farther out. These soft photons are Comptonized and in reality, the photo-dissociation would be done by these Comptonized photons and the synchrotron photons rather than black body photons. We need to compute the number of hard photons above 2 MeV in order to check if this is much larger compared to the deuterium nuclei.

If one considers a pure black body spectrum then the photon number density can be written as,

$$N_\nu^{BB} = \frac{8\pi}{c^3}\left(\frac{kT}{h}\right)^3 \int_{x_m}^{\infty} \frac{x^2 dx}{e^x - 1} \tag{14}$$

where, $x = \frac{h\nu}{kT}$. But the spectrum of photons is not purely blackbody in nature. To calculate the number density of photon in our system we use results of Chakrabarti (1997, hereafter C97). We concentrate on Fig. 4 of C97 where variation of photon spectrum other than black body is discussed. In Fig. 4a of that paper, spectral variation is shown with energy for different values of Keplerian accretion rate (in units of Eddington rate) $\dot{m}_d$. For a complete dissociation of deuterium, at least 2 MeV energy is needed (although with the energy of slightly less than 2 MeV dissociation may start.). We first concentrate on those cases of $\dot{m}_d$ where curves are extended at least to the region greater than 2 MeV. Each of these curves has one peak due to multi-colour black body and the other is a hump due to Comptonization. We concentrate on the hump at higher frequency to compute the number of hard photons. For the dissociation of a helium nuclei one requires a higher energy (~ 32 MeV). In Fig. 4a of C97, except for $\dot{m}_d = 1.5$ where there is a large peak due to the blackbody emission, other cases have significant amount of hard photon. Along with these photons, we include hard photons due to synchrotron radiation as obtained from a standard distribution $\sim I_\nu \sim \nu^{-1.25}$ normalized in a way such that its number is the same as that of the Comptonized photons at the 'knee' where blackbody distribution meets the Comptonized power-law component. This procedure provides a realistic estimate of hard photon. In any case, our main aim is to see if the resulting photon numbers are very large compared to the number of deuterium or helium nuclei. So the exact number is not important.

Following the treatment of Wagoner (1969), we completely turn off the dissociation process if the number of hard photons at a given radius is fewer than about a thousand times that of the deuterium. The same consideration applies for the dissociation of helium nuclei as well.

4. Results

Here we discuss a few results assuming matter falls towards a black hole of mass $10M_\odot$. We choose the polytropic index n to be 3. We assume that the accretion flow consists of both Keplerian and sub-Keplerian matter (Chakrabarti & Titarchuk, 1995). We assume that these two rates are $\dot{m}_d$ and $\dot{m}_h$ respectively and $\dot{m}_d + \dot{m}_h = 2$ for concreteness. We first compute the electron and proton temperatures in the flow by using two temperature hydrodynamic equations numerically (Chakrabarti & Titarchuk, 1995) for different $\dot{m}_d$ and $\dot{m}_h$ rates and

use the resulting (cooler) temperatures to compute nucleosynthesis in our analytical code. Carrying out of nucleosynthesis work in presence of Comptonization would be otherwise very much prohibitive. We verify a posteriori from the solution with nucleosynthesis that such an approximation is valid. In all the three cases listed below we choose $\lambda = 1.6$ and outer edge of the flow at $x_o = 1149$. A flow without nucleosynthesis has a smooth solution passing through the sonic point at 3.05 with these parameters provided it is launched at the outer edge at x_o with a radial velocity $v_o = 8.8566 \times 10^{-5}$ and sound speed $a_o = 0.061966$.

4.1. Case I

Here we choose $\dot{m}_d = 0.05$, $\dot{m}_h = 1.95$. In this case, the photon number density is 1.61×10^{17}/cc. We first check the global behaviour of the infalling matter, such as the position and nature of the sonic points if nucleosynthesis is turned on. Following C89, we plot in Fig. 1a, energy $\mathcal{E}$ at the sonic point as a function of the entropy accretion rate $\dot{\mathcal{M}}$ at these points for a fixed specific angular momentum ($\lambda = 1.6$) of the sub-Keplerian and Keplerian mixture. Dashed curve indicates the behaviour when nucleosynthesis is not included. This behavior is similar to that observed in C89. The solid curve indicates the variation of energy with entropy accretion rate at the sonic point when nucleosynthesis in the flow is included. The dashed curve is shifted vertically by 0.01 in order to see the effects of nucleosynthesis prominently. If the ratio of the number density of photon and the nuclear species to be dissociated in the disk is less than 10^3 the dissociation is turned off because of the deficiency of photons (Wagoner, 1969). For the present set of parameters, it is seen that till $\dot{\mathcal{M}} \sim 10^{-5}$ nucleosynthesis does not affect the sonic points. In the range $\dot{\mathcal{M}} \sim 10^{-5} - 10^{-6}$, the outer sonic points disappear as the solid curve shows a distinct gap in that range where nucleosynthesis is prominent. Subsequently, a new branch is originated. As the inner sonic point is not affected, we can conclude that in these parameters the stability of the disk is not affected. Matter can pass through either the inner sonic point (I) and or through the outer sonic point (O) if the location of the latter point is far enough. Flows with sonic points located at the intermediate distances are unstable.

In Fig. 1b, we show the variation of the Mach number as a function of radial distance. The inner sonic point is chosen at $x_{\rm in} = 3.05$. The velocity of the matter at the outer edge of the disk (assumed at 1149) is chosen to be $v_o = 8.8566 \times 10^{-5}$ as this allows a smooth solution through the inner sonic point when nuclear energy is not included. The long-dashed curve is the resulting solution. The sound speed at the launching point is $a_o = 0.061966$. All quantities are expressed in geometric units. When nucleosynthesis is included, in order that the flow passes through the same inner sonic point smoothly, we had to raise the

sound speed to be $a_o = 0.0791819$. The solid curve indicates this solution. If the flow with nucleosynthesis is given the same $a_o = 0.061966$ as that of the smooth solution without nucleosynthesis (long dashed curve), the resulting solution becomes totally sub-sonic and is unphysical (dash-dotted curve) in the context of black hole accretion. For comparison, we present two other solutions (short dashed and dotted) which begin with different sound speed, and are also found to deviate from the true transonic solution (solid curve). Fig. 2 shows the variation of the energy release due to nucleosynthesis as a function of the logarithmic radial distance of the flow (solid curve). The energy release is basically due to $p-p$ reaction as deuterium burning took place instantaneously after launching the flow. Note that the release is at the most 10^{17} ergs/gm/sec which the specific energy of the flow with an inner sonic point could be around $0.001c^2$ergs/gm. Thus the nuclear cooling time scale is $\sim$ 10s which is large compared to, infall or dynamical time scales $t_d \sim 10^{-3}$s. Thus, energetically nuclear energy release is not significant.

4.2. Case II

Here, we choose a comparatively hotter flow. We use $\dot{m}_d = 0.001$, $\dot{m}_h = 1.999$ photon number density is calculated as 3.02×10^{21}/cc. The global behaviour and particular solutions are shown in Fig. 3(a-b). They have similar properties as those of Case I. In Fig. 3a, we clearly see the disappearance of the outer sonic points between O_1 and O_2. The deviation from a 'non-nuclear' solution is higher, and one requires to launch the flow with a higher speed of sound: $a_o = 0.082167$. In this case, the gas has to be heated at a much higher temperature in order that it may pass through the same sonic point. In that sense the flow is prone to become more unstable than that of Case I. Fig. 2 (dashed curve) shows energy release for this case. A hotter gas releases somewhat higher energy.

4.3. Case III

In this case, we choose a cooler flow so that deuterium is dissociated closer to the black hole. We use $\dot{m}_d = 0.4$, $\dot{m}_h = 1.6$ and specific angular momentum of the mixture of Keplerian and sub-Keplerian gas is $\lambda = 1.6$ as before. Since accretion rate is large, there are virtually no Comptonized hard photons. However, there are synchrotron photons which dissociate deuterium. These synchrotron photons are computed from a power-law intensity distribution with a slope of -1.25 joining with blackbody spectrum at roughly the same place where Comptonized power-law joins. Fig. 2 shows the total energy release (dotted upper curve) as well as energy absorption due to deuterium in this case (dotted, marked by

Q_D). As matter comes closer to the black hole, some deuterium is produced by the $p-p$ reaction which is also instantaneously destroyed. This raises energy absorption closer to a black hole. Note also that only absolute value of Q_D is drawn here.

Fig. 4 gives the variation of the abundance of deuterium, proton and neutron with logarithmic radial distance. In this case, deuterium is totally destroyed at around 100 Schwarzschild radii causing a rise in the protons and neutrons.

5. Concluding remarks

We studied analytically the effects of nucleosynthesis on black hole accretion flows of constant angular momentum. We took only the basic reactions such as $p-p$ reaction producing deuterium and destruction of deuterium and helium due to photo-dissociation since (a) it is easier to handle only a few reactions analytically and (b) these reactions primarily control the energetics of the flow. Since we were dealing with an optically thin flow, the radiation could not be treated as a thermal blackbody and the photon number density had to be calculated from the actual thermal Comptonized spectrum and from synchrotron emission from coronal electrons. Photons with energy higher than the threshold value were used to destroy deuterium and helium.

Though, the energy released or absorbed were found to be not very significant compared to the rest mass of the flow it has a strong influence on the stability properties at the transonic region. For instance, we find that when nucleosynthesis in included, the sound speed of the injected matter must be higher by at least 25 to 30 percent in order that the flow passes through inner sonic point. In other words, the temperature of the flow at the injection point must be 50 to 60 percent higher. If a physical process (such as magnetic heating) could not be found to enable this, the flow will not be transonic and would be unstable (See, Figs. 1b and 3b).

So far, in the literature, study of accretion flows around black holes had been done using two-step numerical procedure — pure hydrodynamics is followed by pure nucleosynthesis and results of nucleosynthesis is fed back into hydrodynamics. This procedure was repeated for the whole disk till a reasonable convergence occurs. In the present paper, we combined hydrodynamics and nucleosynthesis for the first time and studied analytically how nucleosynthesis influences topology of the flow. In some region of the parameter space, the outer sonic point is found to be absent. How would a flow behave in this region? It is conjectured that matter would try to pass through 'some' outer sonic point, becomes supersonic and subsequently pass through the inner sonic point. Since the outer sonic point is not present,

the searching procedure to the true sonic point should give rise to an unstable or oscillating solution. Only a *time dependent* numerical simulation can tell if this conjecture is correct. This will be attempted in the future.

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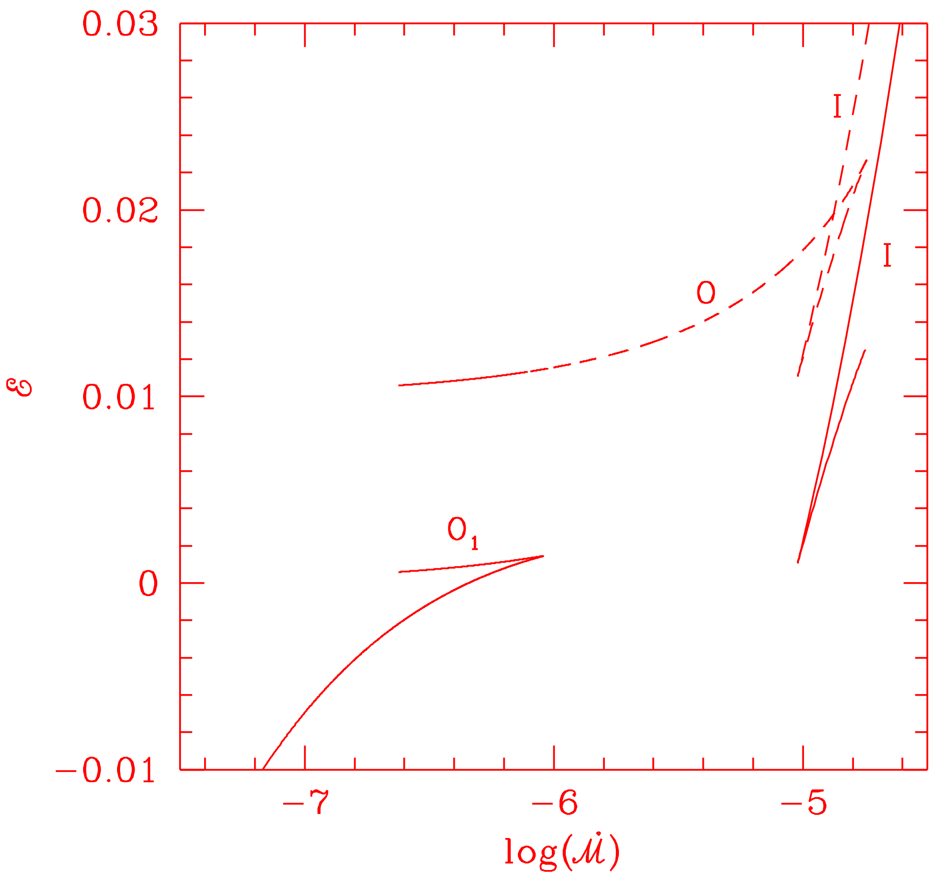

Fig. 1a: Variation of the energy with entropy accretion rate as the sonic points are changed. I and O_1 represent the inner and outer saddle type sonic points and the unmarked curves represent the unphysical 'O' type sonic point. Dashed curve, shifted by 0.01 along energy axis, shows the sonic point behavior when nucleosynthesis is turned off.

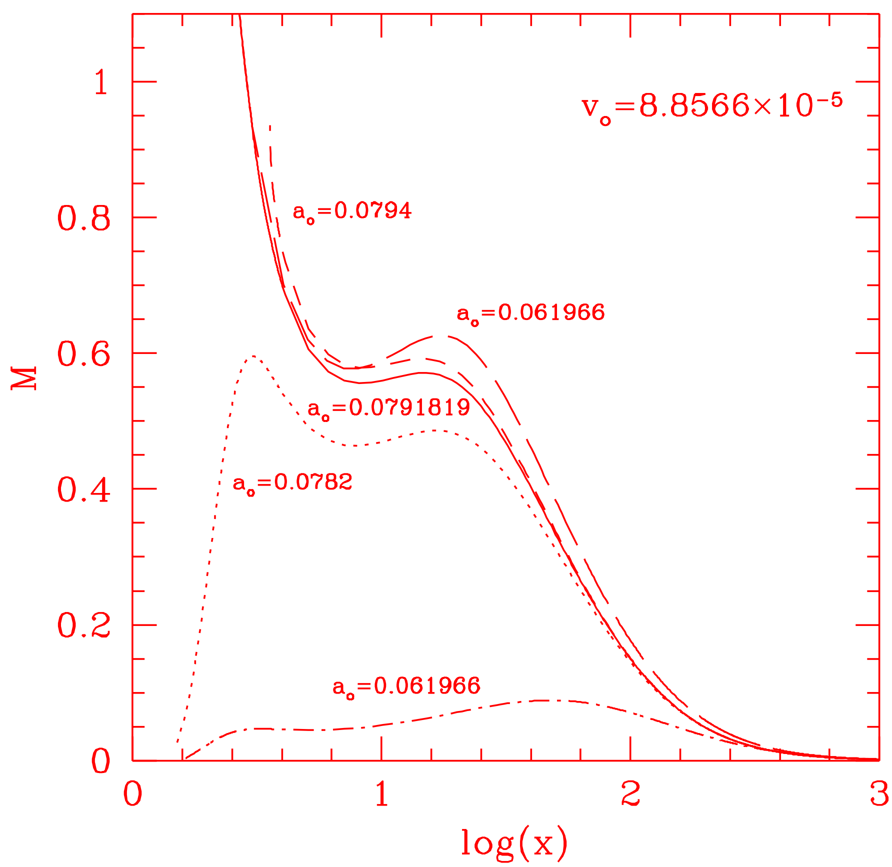

Fig. 1b : Variation of the Mach number of the flow with logarithmic radial distance. Matter injected at $x = 1149$ with radial velocity v_o moves in with injected sound speed $a_0 = 0.061966$ to pass through the inner sonic point when nucleosynthesis is turned off (long-dashed curve). When nucleosynthesis is turned on, sound speed must be modified to $a_0 = 0.0791819$ in order that the flow passes through the inner sonic point (solid curve). Dash-dotted curve is the (unphysical) solution produced when nucleosynthesis is included but the flow had the same initial parameters as that of the long-dashed curve. short-dashed and dotted curves are for some other initial parameters to

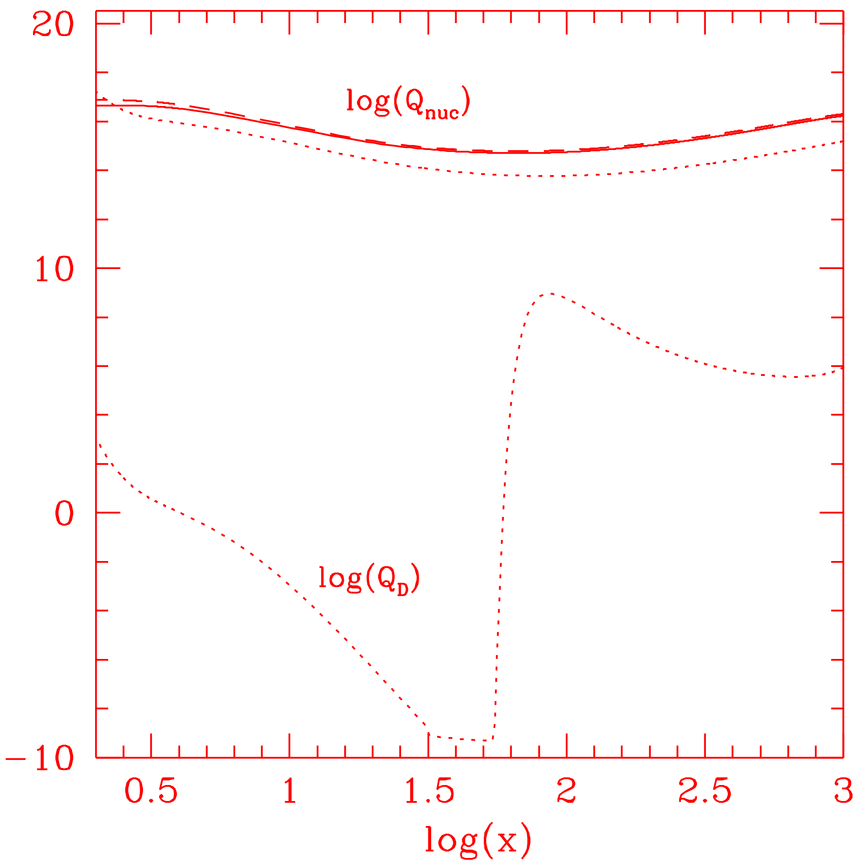

Fig. 2: Variation of net energy release Q_{nuc} (in ergs/gm/sec) as matter is accreted on a black hole. Solid and dashed curves are drawn for cases I and II and the dotted curves are drawn for the case III discussed in the text. Q_D is the energy absorption when deuterium is dissociated.

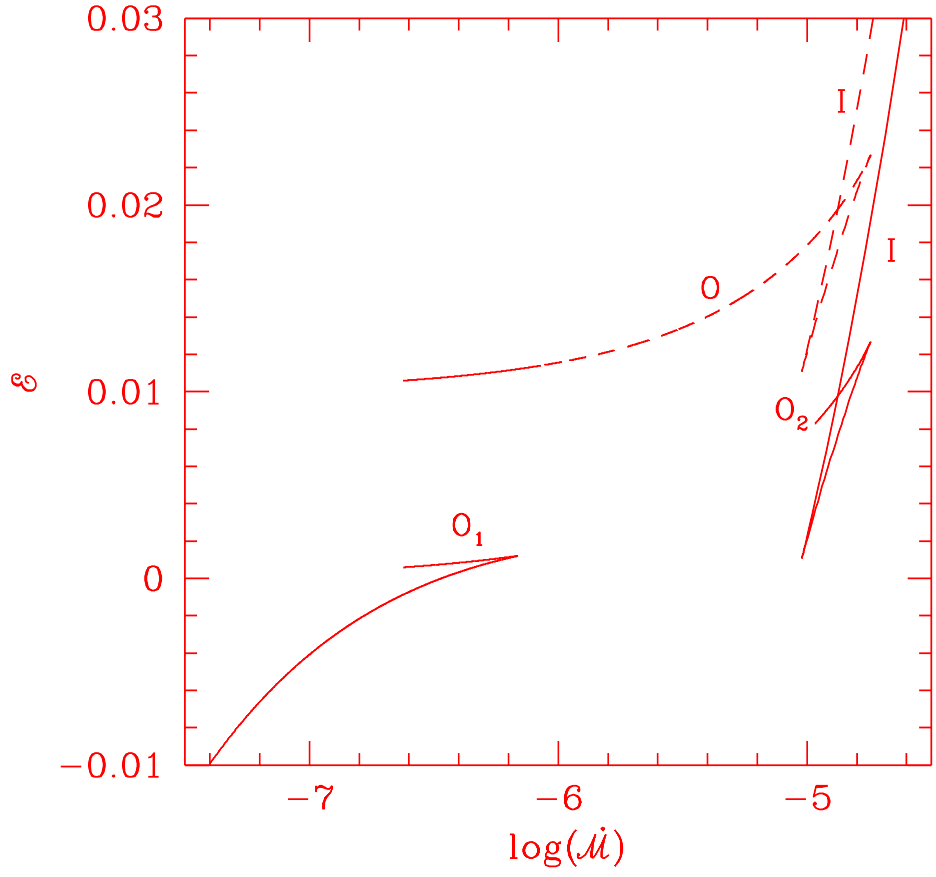

Fig. 3a: Same as Fig. 1a except that the flow is hotter. O_1 and O_2 are outer sonic point branches separated by a gap.

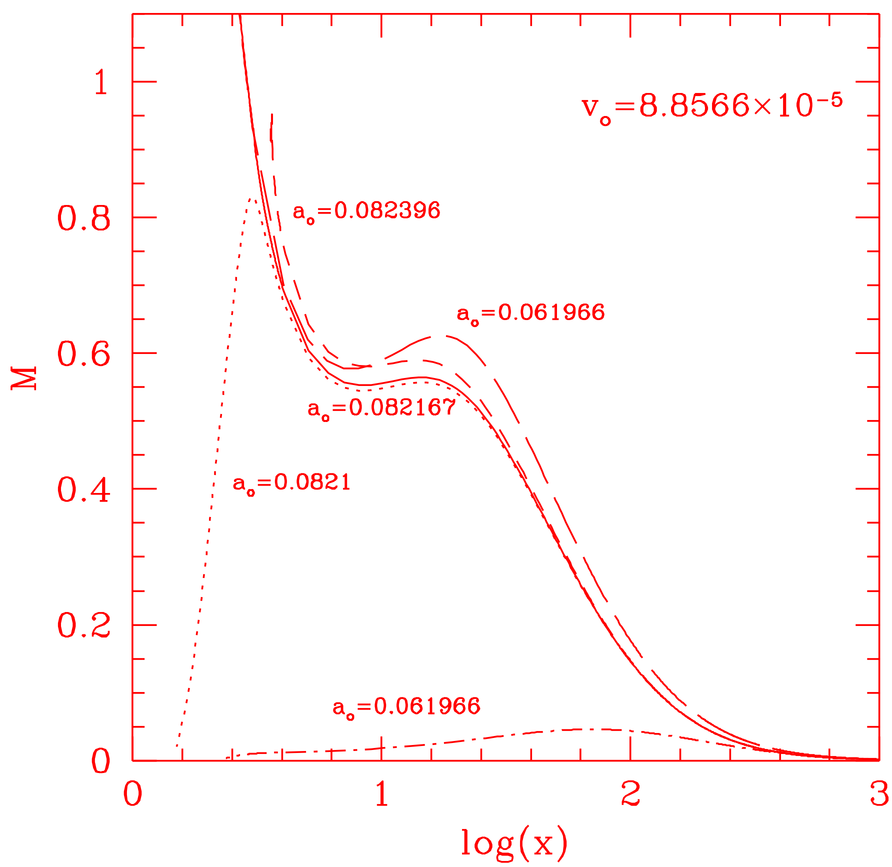

Fig. 3b: Same as in Fig. 1b, except for a hotter flow. In this case, when nucleosynthesis is turned on, the sound speed must be modified to $a_0 = 0.082167$ in order that the flow passes through the inner sonic point (solid curve). See text for details.

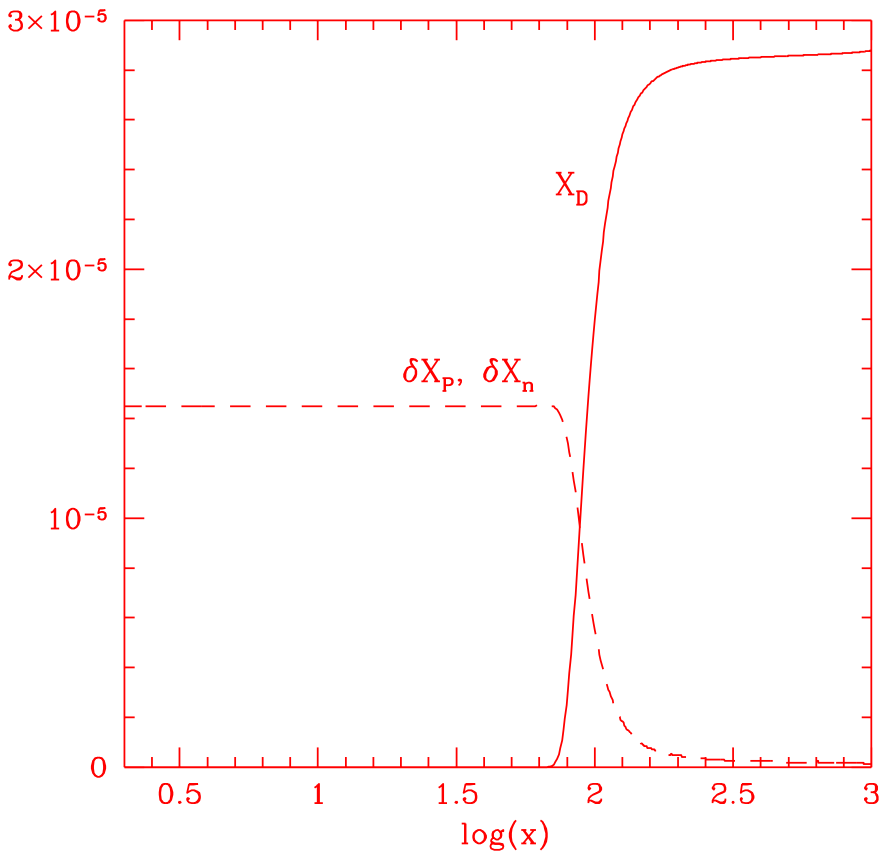

Fig. 4: Destruction of deuterium (X_D), as matter is accreted. Protons and neutrons created because of this are also shown (dashed curve).